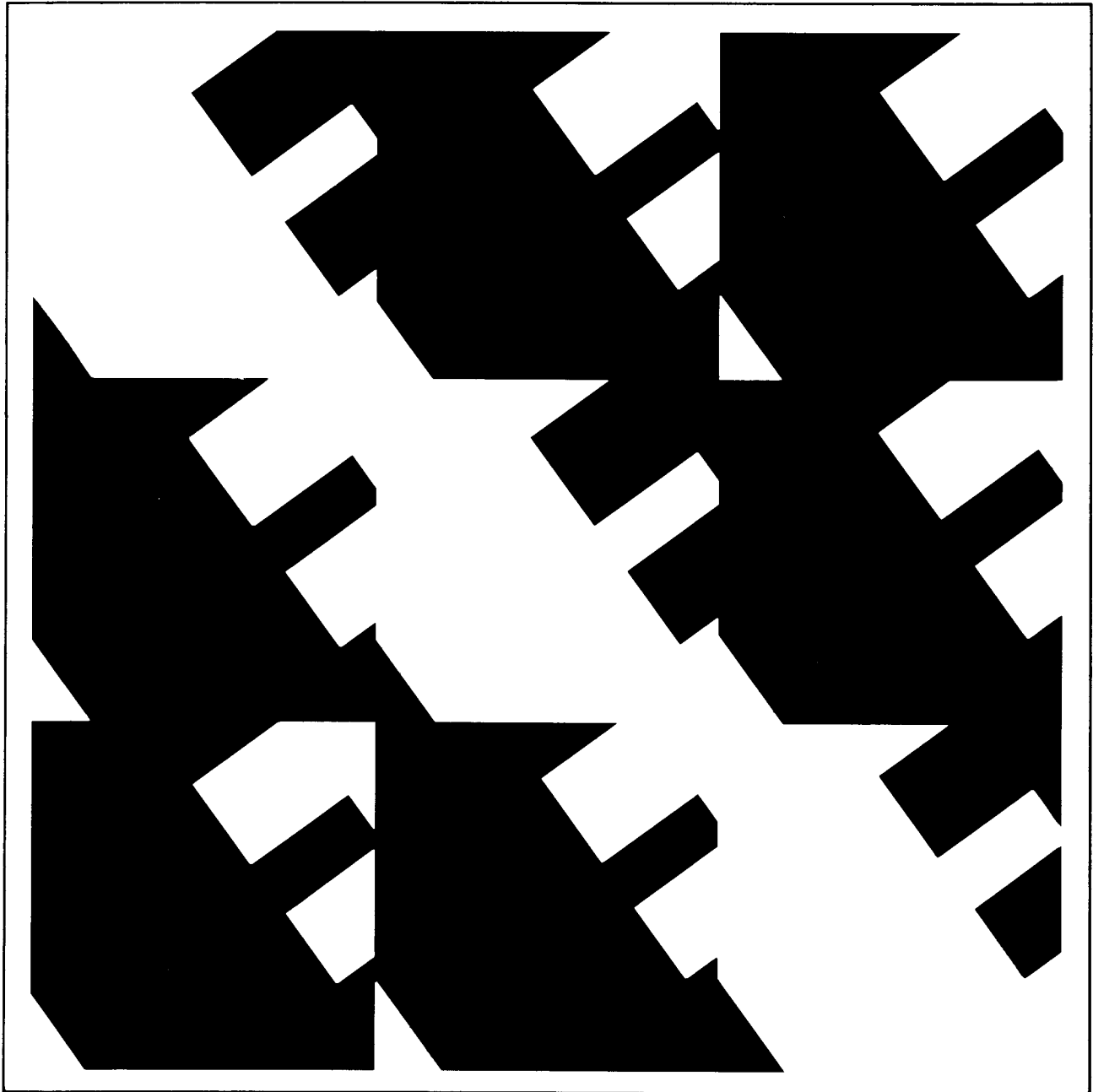


IEEE Guide for Generating Station Grounding



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IEEE Guide for Generating Station Grounding

1. Purpose and Scope

This application document was developed to identify generating station grounding practices that generally have been accepted by the electric utility industry as contributing to a safe and effective grounding system.

This document is intended to provide a guide for the design of generating station grounding including the interconnection of the station and substation grounding systems.

2. Introduction and References

2.1 Introduction. This document pertains to grounding practices applied to generating station indoor and outdoor structures and equipment. It identifies the principal parameters in the selection of acceptable practices for personnel safety and equipment protection. It applies to all generating stations, and it generally reflects current grounding practices in the electrical utility industry. It is intended for use in conjunction with ANSI/IEEE Std 80-1986 [1]¹ and ANSI/IEEE Std 81-1983 [2].

It is not intended that this document provide test methods, mathematical analysis, grounding design, or quantitative analysis of the effects of lightning surges. This document should not be interpreted as requiring any specific design for a particular installation, but is a guide that the designer should recognize and consider.

This document is equipment oriented and includes coverage of grounding practices in four parts:

Grounding of the high-voltage system and generator.

Grounding of generating station auxiliaries, electrical equipment.

Grounding of and lightning protection for generating station structures.

Grounding of buried structures.

A bibliography is also included to provide supplemental information and to document sources of information included herein.

2.2 References. This standard shall be used in conjunction with the following publications:

[1] ANSI/IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding.²

[2] ANSI/IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.

[3] ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

[4] ANSI/IEEE Std 487-1980, IEEE Guide for the Protection of Wire-Line Communications Facilities Serving Electric Power Stations.

[5] ANSI/NFPA 50A-1984, Gaseous Hydrogen Systems.³

¹ The numbers in brackets correspond to those of the references listed in 2.2.

² ANSI/IEEE publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from the Service Center, Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331.

³ ANSI/NFPA publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from Publication Sales, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.

- [6] ANSI/NFPA 77-1982, Static Electricity.
- [7] ANSI/NFPA 78-1983, Lightning Protection Code.
- [8] ANSI/UL 96-1981, Safety Standard for Lightning Protection Components.⁴
- [9] BROWN, G. W. Lightning Performance I—Shielding Failures Simplified. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-97, no 1, Jan/Feb 1978.⁵
- [10] FAGEN, E. J. and LEE, R. H. The Use of Concrete-Enclosed Reinforcing Rods as Grounding Electrodes. *IEEE Transactions on Industry and General Applications*, vol IGA-6, no 4, July/Aug 1970.⁵
- [11] SVERAK, J. G. Simplified Analysis of Electrical Gradients Above a Ground Grid. *IEEE Transactions on Power Apparatus and Systems*, vol PAS 103, no 1, Jan 1984.

3. Definitions

bolted fault. A short circuit or electrical contact between two conductors at different potentials, in which the impedance or resistance between the conductors is essentially zero.

bonding. The permanent joining of metallic parts to form an electrically conductive path that will ensure electrical continuity and the capacity to conduct safely any current likely to be imposed.

bonding jumper. A reliable conductor to ensure the required electrical conductivity between metal parts required to be electrically connected.

continuous enclosure. Refers to a type of isolated-phase bus in which the enclosure is elec-

trically continuous over the full length of the bus. All enclosures are electrically tied together at each end of the bus.

equipment-grounding conductor. The conductor used to connect the noncurrent-carrying metal parts of equipment, raceways, and other enclosures to the service equipment, the service power source(s) ground, or both.

four-wire systems. A three-phase system consisting of three phase conductors and a neutral conductor.

grid mesh. Any one of the open spaces enclosed by the grid conductors.

ground grid (grid). A buried geometric network of interconnected bare conductors.

high-voltage system. An electric system having a maximum root-mean-square ac voltage above 72.5 kV.

isolated-phase bus. A metal-enclosed bus in which each phase conductor is enclosed by an individual metal housing separated from adjacent conductor housings by an air space.

metal-enclosed bus. An assembly of rigid conductors with associated connections, joints, and insulating supports within a grounded metal enclosure.

noncontinuous enclosures. Refers to a type of isolated-phase bus in which the enclosure is sectionalized with insulation between sections to block the longitudinal flow of current in the enclosure.

nonsegregated-phase bus. A metal-enclosed bus in which all phase conductors are in a common metal enclosure without barriers between the phases.

overhead ground wire. An overhead ground wire is a grounded, bare conductor suspended horizontally between supporting rods or masts to provide protection from lightning strokes for structures, equipment, or suspended conductors within the zone of protection created by the masts and overhead ground wire combination.

segregated-phase bus. A metal-enclosed bus in which phase conductors are in a common metal enclosure but are segregated by metal barriers between phases.

station. For the purpose of this document, station is synonymous with generating station.

⁴ ANSI/UL publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from Publication Stock, Underwriters Laboratories, Inc, 333 Pfingsten Rd, Northbrook, IL 60020.

⁵ IEEE publications can be obtained from the Service Center, The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331.

supplementary equipment ground. A grounding conductor used to connect the equipment frame to local grounding system to minimize potential difference.

tolerable voltage difference. The maximum potential difference that would cause a body current to flow of such value as not to cause ventricular fibrillation.

transferred voltage. This is a special case of touch voltage. It is that voltage between points of contact, hand to foot or feet, in a station where the conductor touched is grounded at a remote point or touching at a remote point a conductor connected to the station ground grid. Here the voltage rise encountered due to ground fault conditions may be the full voltage rise of the ground grid and not the fraction of this total, which is encountered in the usual touch contact.

zone of protection. The zone of protection provided by a grounded air terminal, mast, or overhead ground wire is the adjacent space that is essentially immune to direct strokes of lightning.

4. Design Objectives

It is intended that this document identify grounding practices directed toward the achievement of the following design objectives:

- (1) Maintain safe voltages across the station area during high-voltage system transients.
- (2) Provide a low-impedance ground-fault current return path.
- (3) Maintain safe voltages within station structures during electrical transients.
- (4) Minimize noise interference in instrumentation systems.
- (5) Minimize the effects of lightning surges on equipment and structures.

5. Detailed Design Considerations

5.1 Grounding of the High-Voltage and Generator-Voltage Systems

5.1.1 General. The purpose of this section is to provide guidance in the design of the generating station ground grid and station-to-substation ground grid interconnection.

5.1.2 Available Ground-Fault Current. The ground grid design should be based on the maximum

ground-fault current that is expected to occur during the design life of the station. In designing the grid layout, for step and touch voltages the maximum ground-fault current expected to flow between the grid and the earth should be considered.

The total ground-fault current should be separated into the generating station and transmission/distribution system contributions. The ground grid layout should be based on the larger of the two.

The step and touch voltages are determined by the current per meter of ground grid conductor that actually takes an earth path.

When there is a system ground fault remote from the station ground grid, the ground currents from the remote sources do not enter the station grid and therefore do not develop step and touch voltages in the grid area.

Step and touch voltages are not affected by ground-fault current to the generator main transformer(s) when the fault is within the station ground grid, since the current has a metallic return path. However, there may be significant step and touch voltages on the transformer and nearby structures due to the system contribution and metallic path impedance.

No consideration is given in this section to ground-fault currents resulting from the generating station auxiliaries. Faults fed from the secondaries of the unit auxiliaries transformer or the start-up transformer have metallic paths between the source and the fault and thus cannot contribute to ground gradients.

The maximum total ground-fault current availability should be determined for a bolted fault on the substation bus having the highest available fault current in order to size the ground conductors.

The sum of the ground-fault current contributed by the transmission/distribution system and generating station should be considered for sizing the grounding conductors connecting to the ground grid.

Typical values currently range between 35 kA and 45 kA with some systems being designed for 100 kA. These are typical values for large stations, and lesser values may be encountered.

5.1.3 Time to Clear the Ground Fault. Design of bus relaying follows well-established technical procedures. Therefore, the time to clear the initial bus fault plus the time for backup relaying to operate are firm numbers. These numbers should be used in the design. A

typical time to clear a ground fault by backup relays on a high-voltage transmission system is $\frac{1}{3}$ second (20 cycles).

Unrealistic values for time to clear a ground fault result in an excessive amount of buried copper in the ground grid.

5.1.4 Soil Resistivity. One of the most important parameters in designing the station grounding system is the resistivity of the soil in the station area. There are two resistivity values required for the design of a grounding system; one is the resistivity of the surface soil and the other is the average (apparent) resistivity of large volumes of soil. To obtain these values, an extensive soil resistivity survey should be conducted in the station area. The most common test methods are the Wenner Four-Probe Method, which is used to measure large volumes of soil, and the Soil Box Method, which is used to measure soil samples.

Very early in the generating station construction phase, extensive soils exploration is required. Hence, soil boring logs are usually available. Invariably, either a formal soils report is available or a cognizant civil engineer has knowledge of subsurface conditions and the plans for final grading. Frequently, test pits are dug and there is an opportunity to measure subsurface soils directly.

In most temperate regions, it is impractical to design a ground grid where the total length of the conductor (or the equivalent length of ground rods) lies below the frost line. However, experience has shown that ground grids buried at nominal depths of 0.5 to 0.6 m (18 to 24 in) are safe. As an added precaution, the perimeter conductor may be buried below the frost line, or perimeter ground rods may be driven, penetrating the frost line. This has the effect of keeping the overall resistance to earth essentially constant when the ground is frozen.

5.1.5 Preliminary Ground-Grid Layout. A preliminary ground-grid layout may be established once the arrangement of the station is established. No calculations are required for this layout.

Each building should be ringed with a grounding conductor. This conductor can then be used to tie the building steel into the ground grid.

Generally, one or more high-voltage substations are located on the site of the station. The grounding system of the substations should be tied into the generating station ground grid where practical.

An estimate of the length of grounding conductor to be installed within the substation should be obtained.

Where practical, the ties between the station ground grid and the substation ground grid should include grounding conductors installed directly under the tie line to the generator transformer.

Occasionally, the high-voltage substations are located thousands of feet from the generator transformer, and it becomes impractical to tie the substation ground grid and generating station ground grid together. This can present some potentially serious problems, as discussed in 5.4.6.

Assuming the substation ground grid is designed to be separate from the generating station ground grid, the generating station ground grid should be designed for a ground fault on the high-voltage side of the generator transformer.

Any interconnections between the two ground grids (control wiring, multiplexing leads, telephone lines, etcetera) can be subjected to the difference in potentials between the two ground grids. Under fault conditions, potential differences of 5 kV or more are not uncommon.

Even if the remote substation ground grid is tied to the generating station ground grid, there may be significant potential differences between the two grids due to inductive effects.

Interconnecting the ground-grid perimeter, buildings, and substation completes the preliminary design.

5.1.6 Resistance to Earth. The design resistance is useful in estimating the magnitude of voltage expected to appear between the station equipment and equipment located external to the station area.

Some designers prefer to limit the overall voltage rise to 5 kV. However, in high-resistivity soils this limit may require excessive ground grid area. Limiting the grid to some voltage rise rarely improves the safety of the grid, since safety is largely a function of available step and touch voltages. However, some telephone companies may request a specific limit to safeguard their equipment. The full grid voltage rise appears between the plant telephone system and the off-site telephone lines. Telephone lines are also affected by line induction during fault conditions.

Ground-grid resistance is calculated using the ground-grid area and length of grounding con-

ductors of the preliminary layout coupled with the assumed value of soil resistivity.

The effect of other buried materials is discussed in 5.1.17.

5.1.7 Ground Rods Versus Ground Grid.

Some designers prefer to use a ground grid that consists entirely of bare conductors; others prefer a combination of bare conductors with ground rods, while still others prefer to use deep rods with insulated conductors. All methods are acceptable, but the calculations required for ground rod system analysis are more difficult, and care should be taken to ensure that tolerable step and touch voltages are achieved, particularly where insulated conductors are used. Confirmation of a ground rod system design can best be obtained by simulated ground fault tests.

Consideration should be given to the selection of grounding materials that will minimize corrosion.

5.1.8 Touch Voltage. The maximum touch voltage (the mesh voltage) within a grid mesh is the voltage difference between the grounding conductor and the earth in the center of that grid mesh. An example would be a person standing equidistant from surrounding grounding conductors and operating a valve on an above-ground pipe.

The tolerable touch voltage difference depends on many variables such as the resistivity of the soil (or other material such as rock or concrete) on which the person is standing, the clearing time of the fault, etcetera.

The actual touch voltage can be calculated and depends on the resistivity of the soil surrounding the grounding conductor, the ground fault current, the length of buried grounding conductor and two coefficients, K_m and K_i , as referenced in 5.1.10.

Safe design requires the calculated touch voltage to be less than the tolerable touch voltage.

If the preliminary design is not adequate, then additional length of grounding conductors should be added to lower the value of mesh voltage and make the design safer.

5.1.9 Step Voltage. The tolerable step voltage difference depends on many variables such as the resistivity of the soil (or other material) in contact with the feet, time duration of the fault, etcetera.

Step voltages rarely become a design consideration because the tolerable touch voltage difference is so much lower. However, step voltages at the grid perimeter should be calculated to

confirm this.

The actual step voltage can be calculated given the soil resistivity in contact with the feet, the ground fault current, the length of buried grounding conductors and two coefficients, K_s and K_i , as referenced in 5.1.10.

For a safe design, the calculated step voltage should be less than the tolerable step voltage difference.

5.1.10 Calculation Coefficients K_m , K_s , and K_i . K_m , K_s , and K_i are coefficients that are defined and used in various formulas appearing in ANSI/IEEE Std 80-1986 [1]. $K_m K_i$ are used in calculating the touch voltage. $K_s K_i$ are used in calculating the step voltage.

ANSI/IEEE Std 80-1986 [1] allows the determination of step and touch voltage coefficients by three methods: based on suggested values, based on models, and based on equations.

Laurent suggests a value of 0.1 to 0.15 for $K_s K_i$. Niemann suggests a value of about 1.2 to 1.3 for K_i . Laurent recommends values of 1 for $K_m K_i$.

Experiments with models of various ground grid configurations indicate maximum values of $K_m K_i$ ranging between 1.73 and 2.23.

Equations are given in ANSI/IEEE Std 80-1986 [1] and in other references such as "Simplified Analysis of Electrical Gradients Above a Ground Grid" [11] for the determination of K_i , K_m , and K_s . However, great care should be taken with these equations because they yield considerably higher coefficients for large grid meshes typically over 150 m (500 ft) wide, which are associated with generating stations covering large areas.

5.1.11 Voltage Gradients Under Transmission Lines. Voltage gradients in the substation and particularly where the transmission lines cross the station perimeter grounding conductor will be much steeper than at locations remote from the high-voltage bus and lines.

This is the result of ground fault current tending to concentrate itself in close proximity to the power conductor feeding the fault. Grounding conductors within the ground grid should therefore be provided under all high-voltage lines, where practical.

5.1.12 Overhead Ground Wires. Incoming transmission lines generally have one or two overhead ground wires for lightning protection of the lines.

Some utility systems electrically isolate the overhead ground wire from the generating sta-

tion ground grid by means of a series insulator in the overhead ground wire, between the substation structure and the first tower outside the ground grid. Although there may be valid reasons for isolating the overhead ground wire from the ground grid, it should be noted that steep gradients can be expected at the bases of the first few towers outside the ground grid that result from the overhead ground wire fault current being forced into the ground at the base of the tower.

When the overhead ground wire is tied into the ground grid, the first tower outside the ground grid may still carry considerable ground fault current.

It is permissible to deduct the overhead ground wire current from the ground fault current for step and touch voltage calculations if the overhead ground wire is tied directly to the ground grid. Methods exist for these calculations and they should be available from the transmission line designers, who check the ground wire current-carrying capability under fault conditions.

5.1.13 Grounding Conductor Size. Wire size may be calculated using ANSI/IEEE Std 80-1986 [1]. This implies that any conductor and its joints in the grid are capable of conducting the entire ground fault current without exceeding a specified temperature, depending on the type of connectors used.

Smaller conductor sizes or conductors of materials other than copper can be justified if division of ground currents within the grid can be determined.

For mechanical reasons, grounding grid conductors are rarely smaller than 4/0.

5.1.14 Transferred Voltages. Voltages can be transferred outside the ground grid by railroad tracks, metallic pipes, conduit, low-voltage neutral circuits, communication circuits, and fence sections that may extend past the limits of the ground grid. While the main concern is with the transfer of ground grid voltage outside the station, transfer of voltages can also occur within a generating station site, particularly if the site is quite extensive.

Where the possibility of transferring voltages exists, a means of ensuring safe values of step and touch voltages should be provided. Insulating structures at the perimeter of the ground grid is one possibility (for details see 5.4 and Fig 3).

5.1.15 Crushed Rock. It is common in the design of substation ground grids to specify high-resistivity crushed rock surfacing for the entire substation area. While this is both effective and practical for the limited area of the substation, it is not practical for the entire generating station area.

5.1.16 Testing. Frequently, test requirements for a completed ground grid consist of measurement of the final resistance to ground. As indicated earlier, resistance to ground is rarely a measure of the safety of the grid. When the safety of the grid design is questioned, the touch and step voltages should be tested.

The most commonly used test method to determine resistance to ground is the Wenner Three-Pin Method. The measurement of touch and step voltages most frequently employs a simulated ground fault test.

The Wenner Three-Pin Method consists of connections to the ground grid, a current pin, and a potential pin.

Great care should be used when testing using the three-pin method. It is not uncommon to have completed grid resistances in the low hundredths of an ohm (even though calculations may suggest tenths of an ohm). This makes instrument and measurement techniques critical.

Buried water pipes or railroad tracks paralleling or crossing the test leads can result in inaccurate measurements. Great measurement distances out from the perimeter of the ground grid are required; distances of over 900 m (3000 ft) are not uncommon. Railroad tracks, trees, roads, and lay-down areas (areas used for storage of large equipment prior to installation) frequently make this test difficult.

The use of modern, high-resolution ground-resistance testers overcomes many of the problems associated with taking measurements on large, low-resistance ground grids.

Frequently, in the construction of a generating station, there are opportunities for simulated ground fault testing utilizing new transmission lines built but not yet energized.

Ideally, simulated ground fault testing requires a source of ground fault current (one phase of a 480 V construction power transformer can be used), a remote ground for grounding the transformer phase such as an unenergized transmission line that can be grounded at least 7 or 8 km (4 or 5 miles) from the station, and a connection to remote ground (another unenergized

transmission line), preferably at right angles to the grounded phase.

Measurements of a simulated ground fault ideally should include current on the faulted phase, voltage of the faulted phase, voltage rise to remote earth, current in the overhead ground wires, and voltage gradients of the earth at locations suspected of having high-voltage gradients (under transmission lines, at points or projections of the grid, and measurements to the center of one or more of the largest meshes).

The Fall-of-Potential method is another common test method for measuring the resistance of a station ground. This method involves the measurement of the voltage difference of the station ground with respect to a reference electrode while current is being circulated between the station ground and an auxiliary (test) ground. Both the reference electrode and the auxiliary ground should be placed in a remote area from the station ground. Remote is considered an area that is outside the area of influence surrounding the station ground while the test current is being circulated. For the detailed procedure, refer to ANSI/IEEE Std 81-1983 [2].

Note that the *resistance* of large grounds (such as a station ground) contains a significant reactance and therefore the results of the tests should be expressed in impedance rather than resistance.

5.1.17 Differences Between Generating Station Ground Grids and Substation Ground Grids. Generating station grounding is principally designed to assure tolerable touch voltages on generating station structures and equipment. A grid to control touch and step voltages is important in the area surrounding the generator, unit service transformers, and station service transformers, but should also be considered wherever there may be high concentrations of ground fault current.

Generating station ground grids differ from substation ground grids in a number of ways.

Probably the most important difference is in the number of grounded structures in contact with the earth for which no credit can be taken in the design unless actual tests on the installed facility verify their effectiveness. For example, the reinforced concrete base slabs of buildings are very likely large contributors to the effectiveness of the overall ground grid.

Circulating water intake structures with their associated submerged bar-racks, traveling

screens, and pumps provide additional grounding.

A single water well can provide a resistance to earth of a fraction of an ohm. Buried bare metallic pipe, conduit, piles, etcetera, also contribute to the effectiveness of the grounding system.

5.1.18 Generator Grounding. On unit-connected systems, main generator neutrals are usually connected to ground through the primary of a single phase transformer. A resistor is connected across the secondary of the transformer, to provide a high-resistance neutral ground connection. The resistor and transformer are sized to produce an equivalent ground resistance numerically equal to or less than the total three-phase capacitive reactance to ground of the generator and other equipment connected at the generator voltage level. The ground resistance may be reduced below this value if necessary to supply the current required for proper coordination with potential transformer fuses.

Most faults originate as phase-to-ground faults. Protective relays are usually connected to initiate a generator shutdown on detection of a ground fault.

The coincident occurrence of a ground fault in the generator with a ground fault in another phase of connected equipment beyond the generator terminals could produce a phase-to-phase fault current flowing through the generator frame ground connections equal to the combined phase fault contributions of the system, the generator, and the station auxiliaries. The system contributions typically will be interrupted within 20 cycles by protective devices while, depending on the fault location, the generator contribution may decay over a period of several seconds, as determined by machine time constants and the method of excitation removal.

Multiple ground connections adequate to carry this current for the fault duration should be provided from the station ground grid to terminals provided by the manufacturer on the generator frame, and to the other connected equipment such as isolated phase bus shorting plates and transformer tanks. There should be no direct bonding connection between the generator frame and isolated phase bus shorting plates, enclosure, or ground bus.

The enclosure for the generator neutral bus, including the connection from the enclosure to

the neutral grounding equipment, should not be bonded to the generator frame and should be separately connected to the station ground grid.

Manufacturers' recommendations should be followed for the grounding of turbine or other prime-mover casings.

The shaft of steam turbines should be grounded in accordance with manufacturers' recommendations. Care should be taken to avoid shorting out insulated bearing pedestals and shaft seal carriers so as to prevent shaft circulating currents.

The exciter and all other auxiliaries associated with the generator should be grounded if they are not adequately bonded to the generator frame.

Smaller generators frequently have their neutrals grounded through resistors or reactors. If shielded cables rather than isolated phase bus are used for the line terminal connections, then the cable support system and any shield ground connections at the generator terminals should be insulated from the generator frame.

5.1.19 Isolated Phase Bus Grounding

5.1.19.1 Isolated Phase, General Comments. A generally accepted method of connecting a generator to the generator transformer, auxiliary transformers, surge protection equipment, and the potential transformer is by means of isolated phase bus. The generator neutral connection and the connection to the generator neutral grounding equipment may also be isolated phase bus.

Present practice is for the isolated phase bus enclosure to be insulated from the generator frame. An insulated joint is usually used where the enclosure bolts to the transformer throat.

Ground fault current in the isolated phase bus associated with main power connections to the generator is usually limited to very low values by the generator neutral grounding equipment.

A phase-to-phase fault cannot occur in isolated phase bus. Simultaneous phase-to-ground faults in the bus and in connected equipment could result in very large phase-to-phase fault current, which would flow through the equipment grounding conductors and the ground grid.

5.1.19.2 Continuous Enclosure Isolated Phase Bus. A continuous enclosure acts as a low-resistance ground bus extending the full length of the bus assembly.

The enclosure should be grounded at all ends at the point where the bus enclosures are electrically tied together. At ends where the en-

closure is insulated from the connected equipment, the connection to ground should be sized to carry the maximum fault current plus any enclosure unbalance current at the location under consideration.

Indoor supports as required can be fastened directly to the building steel or bonded to the building ground grid.

Outdoor supports should be grounded by a connection to the ground grid at the base of each support column.

5.1.19.3 Noncontinuous Enclosure Isolated Phase Bus. Isolated phase bus with noncontinuous enclosures includes a ground bus running the full length of the bus assembly. Each enclosure section is usually connected to the ground bus at one point only and the ground bus is sized to carry the maximum fault current that could flow in the section of bus it parallels. However, manufacturers' recommendations should be followed in specific applications.

The ground bus should be grounded at all ends of the bus assembly. At ends where the enclosures are insulated from the connected equipment, the connection to ground should be sized to carry the maximum fault current at the location under consideration.

Indoor supports as required between bus supporting frame and the building steel should be electrically continuous.

Outdoor supports should be grounded by a connection to the ground grid at the base of each support column.

Circulating currents may flow in the ground bus and in the supporting structure of isolated phase bus with noncontinuous enclosures. In a properly designed bus, this current will be relatively small and will not cause an objectionable temperature rise.

There will be a voltage across the insulated joint between the enclosure sections in isolated phase bus with noncontinuous enclosures. With high fault currents and long enclosure sections, this voltage may exceed the tolerable voltage difference, and this should be considered in the design of the bus.

5.1.20 Grounding Segregated and Non-segregated Phase Bus. A ground bus or its equivalent should run the full length of the bus. The bus enclosure may be used as the equivalent to the ground bus, providing that adjacent enclosures are suitably bonded and the enclosure has the capacity to carry the maximum fault current.

Indoor supports as required can be fastened directly to the building steel.

Outdoor supports should be grounded by a connection to the ground grid at the base of each support column.

The ground bus should be connected to the ground bus of all connected equipment and to the ground grid. Where the equipment ground bus and its connection to the ground grid have adequate capacity, the separate connection to the ground grid may be omitted.

5.2 Grounding of Generating Station Auxiliaries, Electrical Equipment

5.2.1 General. The purpose of this section is to provide guidance for grounding of electrical equipment associated with the generating station auxiliaries.

5.2.2 Station Service Power Source Grounding. Design of grounding for generating station service power sources uses several different approaches. The power sources may be solidly grounded, ungrounded, or grounded through resistance or impedance. The resistance may be selected to limit ground fault current to as low as a few amperes. In some applications, the fault current is low enough that breaker tripping on a single ground fault is not required.

The grounding approach used at each voltage level may differ. For example, it may be desirable to use medium-resistance grounding at the highest voltage level to limit the ground fault current and limit damage under fault conditions; high-resistance grounding at an intermediate voltage level to permit continued operation; and low-resistance grounding at low voltage levels where plant reliability is not adversely affected by equipment tripping.

The performance requirements for the electrical equipment ground are similar, regardless of the system grounding scheme employed. The impedance of the return path to the power source for ground fault current must be kept low. Where breakers are tripped under ground fault conditions, low impedance of the return path is necessary to ensure rapid tripping of the breakers. In cases where the breakers are to remain closed under ground fault conditions, that is, a high-resistance grounding system, the low-impedance return path is essential to provide proper relay action to alert station personnel that the fault condition exists.

Similar considerations apply to the grounding of equipment in dc systems.

5.2.3 Purposes of Grounding Electrical Equipment. The grounding of electrical equipment serves two purposes, as defined below.

The grounding conductor routed with the power conductors provides a low-impedance path between the equipment frame and the power-source ground.

The grounding conductor can be a continuous conductor or a combination of raceway, jumpers, and conductors to form a reliable metallic ground return path in close proximity to the power conductors to minimize the impedance to ground fault current.

The supplementary ground conductor provides a low-impedance path between the equipment frame and the station ground grid.

Both connections are usually required to provide reliable ground fault current flow and to prevent voltage differences between faulted equipment and adjacent grounded metal. There may be applications where the supplementary ground is not required (for example, for small loads in inaccessible locations, or where the equipment mounting arrangement provides an adequate ground path to adjacent structural members).

5.2.4 Electrical Equipment Grounding Requirements. The grounding system design should meet the highest ground fault current requirements under any possible operating configuration. The design should consider the distribution system protective trip settings and clearing time as well as the maximum possible ground current. It should prevent deterioration of the grounding conductors and connections under repeated ground fault conditions. The design should also minimize corrosion and protect the system against mechanical damage throughout the life of the generating station.

5.2.5 Grounding Conductor Sizing. For a solidly grounded system, the grounding conductor should be sized to carry phase-to-ground current for the time required to clear the ground fault by backup protection.

Resistance grounding may be either high-resistance or low-resistance, distinguished by the magnitude of ground fault current permitted to flow. In a low-resistance grounded system, the fault current is high enough that breaker tripping on a single ground fault is required to minimize damage. If ground fault relays are not used on individual feeders, the ground fault current should be adequate to trip the largest feeder not having a ground fault relay. In a high-resistance

grounded system, the fault current is limited to a minimum value as determined by the total capacitance charging current. A ground fault trip scheme or a ground fault alarm scheme may be used on a high-resistance grounded system.

A ground fault trip scheme will initiate a breaker trip on detection of any single ground fault. The grounding conductors shall be sized to carry current as determined by resistor size and have sufficient mechanical strength to withstand physical damage. Since all ground faults will be cleared promptly, phase-to-phase fault current carrying capacity for the grounding conductor is not required.

A ground fault alarm scheme will initiate an alarm but will not initiate a breaker trip on detection of a ground fault. When a ground fault alarm scheme is used, the grounding conductor should be sized to carry phase-to-phase fault current for the time required to clear a double phase-to-ground fault. The grounding conductor should have low impedance to ensure immediate operation of phase overcurrent protection due to double phase-to-ground faults.

Consideration should be given to possible double phase-to-ground faults in ungrounded and high-impedance grounded systems provided with a ground fault alarm only. Any possible double phase-to-ground fault path through the conduits, cable trays, or metallic frame grounding connections should have sufficiently low impedance to ensure operation of phase overcurrent protection and have sufficient current-carrying capacity to conduct the double phase-to-ground fault current for the time required to clear the fault.

5.2.6 Types of Equipment Grounding Conductors. The following are acceptable types of equipment grounding conductors, provided that they are electrically continuous and capable of carrying design fault current throughout their entire length from source to load.

A conductor within the same raceway or cable as the circuit conductor.

A metallic raceway enclosing the circuit conductors using fittings for joints and terminations approved for use with the type of raceway used. The raceway should have adequate cross-sectional area of metal to carry the design fault current of the largest circuit carried in the conduit or raceway.

Cable trays carrying the circuit conductors, provided the trays are grounded in accordance with 5.2.7.

A cable tray may be used as a common equipment grounding conductor for any cables supported in that tray.

5.2.7 Specific Electrical Equipment Grounding Requirements. The tanks of transformers that act as power sources for portions of the station service system should be grounded to the station ground grid by separate grounding conductors (supplementary grounds). If the distribution system is designed to be operated as a solidly grounded system, the neutral of the secondary winding should be connected directly to the station ground grid. If the station service system is designed to be operated as a low- or high-resistance grounded system, the secondary winding should be connected through a grounding resistor or a grounding transformer with secondary resistor to the station ground grid.

Within switchgear, a ground bus should be installed in an accessible location for the total length of the switchgear in order to electrically connect all of the switchgear steel and power cable shielding. The ground bus is connected to the station ground grid by means of grounding conductors. If a four-wire system is used, a neutral bus, insulated from ground, should also be installed in an accessible location for the total length of the switchgear. The purpose of the neutral bus is to provide a place to connect the neutral of the source transformer to the neutral conductors of the outgoing feeder cables. The transformer neutral should be grounded near the source only. This grounding conductor should be separate from the ground bus grounding conductors.

Within motor control centers, a ground bus should be installed in an accessible location for the total length of the motor control center. The purpose of this bus is to electrically connect all of the motor control center steel to the ground bus. The ground bus is connected to the station ground grid by means of grounding conductors. If a four-wire system is used, a neutral bus, insulated from the ground bus, should also be installed in an accessible location for the total length of the motor control center. The purpose of the neutral bus is to connect the neutrals of all incoming and outgoing feeder cables.

The cable support system consisting of cable trays, raceways, etcetera, should be bonded to the local building steel or the ground grid at intervals to limit touch voltages to safe levels.

Cable tray sections should be bonded together, as well as to all associated conduits, switchgear,

or motor control center ground buses.

If the cable tray system is used as an equipment grounding conductor, the cable tray, the bonding between sections, and bonding to source and load should be capable of carrying the largest fault current.

If the cable tray connectors used are not suitable as bonding connectors, additional bonding is required.

Control cables in general are not required to include a grounding conductor, provided that the cable support system and equipment are adequately bonded and grounded. Shielded control cables in the generating station should have the shield of each control cable section grounded at one end only to prevent circulating ground currents; adequate means of grounding the shield should be available, such as provision of a drain wire. Other requirements apply for shielded control cables exposed to high-energy transients in substations, as outlined in 5.4.6.

Shielded instrumentation cables (millivolt or milliamp signals) should have their shields electrically isolated from ground except at one point where a single ground conductor runs to the station ground, thus preventing ground current interferences.

For control equipment, a single point ground is desirable. Consoles, racks, trays, frames, and panels should be provided with a grounding connection. Where two different power supplies with individual single point grounds are brought to the control equipment, interconnections between the ground points should be avoided.

In circuits where electrical connections are required from relays to a complex electronic package, it is preferable to enclose the relays and electronic components in a metal case or frame to ensure that adequate shielding is provided. The metal case or frame should be grounded, and internal circuits should be isolated from the metal frame. Components such as capacitors and resistors requiring a common ground should have a special ground connection isolated from the metal case. The metal case or frame is not acceptable as a return conductor.

All motors are usually required to have two grounded connections: the first, the equipment ground, is a ground conductor or shield run with the circuit conductors feeding the motor; the second, the supplementary equipment ground, should be a visible connection between the motor frame and the surrounding structural steel, the station ground grid, or both. The supplementary

ground may not be required for small motors in inaccessible locations or where the mounting arrangement provides an adequate ground path to adjacent structural members.

When the shield is to be used as the grounding conductor, it should be rated to carry ground fault current for adequate time to trip a backup breaker without shield damage.

5.2.8 Grounding of Auxiliary Buildings.

Auxiliary buildings such as pumphouses, coal sheds, etcetera, located away from the generating station should be provided with two independent ground connections.

A supplementary equipment ground conductor should be provided around the perimeter of the building and all structural steel, panels, metallic frames, etcetera, should be connected to this ground conductor; the conductor itself should be connected to the station ground grid. If this is impractical, precautions should be taken to prevent transfer of voltages.

A second independent ground conductor should lead into the building with the power source to provide the equipment ground for electrical equipment installed inside the building. This conductor is the grounding conductor and should not be used as the neutral ground of a four-wire system. It should be connected to the auxiliary building ground conductor. It is important that the equipment ground conductor be kept near the circuit conductors. This will minimize the impedance of the ground path, thus limiting the voltage rise of the auxiliary building grounding system.

5.3 Grounding of and Lightning Protection for the Generating Station Structures

5.3.1 General. The purpose of this section is to provide guidance for the grounding of and lightning protection for generating station structures. It is the intent that the material presented herein serve as a guide for establishing requirements for any station. Where special needs arise, other documents are cited in Section 6.

Lightning produces both direct effects and indirect effects. The direct effects include burning, blasting, ignition of combustibles, electrocution, and other obvious manifestations of lightning. This document discusses practices to protect against these direct effects. The indirect effects involve the electromagnetic fields resulting from large currents associated with lightning. Indirect effects can damage or cause misoperation of control equipment with consequences more

costly than the direct effects. This document is not intended to deal with indirect effects.

5.3.2 Types of Structures. The typical generating station is composed of many different types of structures that vary in material construction and usage. These varying types of material and usage largely determine the extent and method of grounding and lightning protection to be used.

Structure grounding is done for two reasons: to provide safety for personnel, and to provide protection for buildings and associated installations. Care should be taken to avoid excessive increases in voltage during faults and static discharges such as lightning.

Metal buildings and structures may offer a satisfactory discharge path for lightning strokes provided certain conditions are met (see 5.3.5) and may require nothing more than providing multiple grounds at the structure base.

Nonmetallic structures composed mostly of nonconducting materials may require an extensive lightning-protection system.

Structure usage should be considered in the choice of lightning-protection method. For a structure providing a very important function such as a microwave tower, more extensive lightning protection may be required than for a structure such as a minor storage building.

The following types of structures will be considered in this document:

- All-metal structures
- Buildings for equipment and personnel
- Tanks
- Substation structures
- Exposed piping
- Railroads
- Fences
- Communication tower
- Stacks
- Case grounding for outdoor equipment
- Metal structures with thin metallic siding
- Nonconducting structures
- Buildings for equipment and personnel
- Chimneys
- Cooling towers
- Containment buildings
- Combination metallic and nonmetallic structures
- Metal structures with a nonconducting exterior
- Nonconducting structure with a metallic skin or projections

5.3.3 Factors Governing the Decision Whether or Not to Provide Lightning Protection. In establishing the requirement for and extent of lightning-protection design, the following factors should be taken into account.

5.3.3.1 Frequency and Severity of Thunderstorms. The average number of storms per year may reach ninety in some areas of the United States and may be as few as five in other areas. This information may be obtained from appropriate isokeraunic maps for the area. In some areas, the severity of storms is much greater than others and is not directly related to the frequency. A few severe thunderstorms a season may make the need for protection greater than a relatively large number of storms of lighter intensity.

5.3.3.2 Value of the Building and Contents

5.3.3.3 Personnel Hazards. Casualties within buildings are rare because of the shielding effect provided by the structural materials in most buildings. Many buildings, however, exist with less desirable shielding material, and a stroke of lightning to such a building constitutes a serious danger to the occupants.

5.3.3.4 Exposure. The relative exposure of a building to lightning strokes should be considered. A building surrounded by other tall structures is much less exposed to lightning strokes than a building in open terrain since the lightning strokes may be diverted to the other tall structures. In essence, a zone of protection exists around a structure defined in a similar manner as that around masts or overhead ground wires (see 5.3.5). Thus an outlying pump structure may be more exposed than buildings near the stack at a fossil-fueled station or near other tall buildings.

5.3.3.5 Economics. Probably the most important consideration on the generating station site is the cost of the indirect losses. If lightning causes a forced shutdown of a generating station, the economic consequences are almost always greater than the direct loss incurred. This should be taken into consideration in designing the lightning-protection system.

5.3.3.6 Regulatory Requirements. Factors essentially independent of the other considerations are regulatory and insurance-carrier requirements.

5.3.4 Planning an Air Terminal Lightning-Protection System. The most frequently used lightning-protection method for buildings is the

air terminal system. Air terminal protection consists of a grouping of short masts (air terminals) at proper locations on a structure. When making plans for a lightning-protection system of the air-terminal type, the following conditions should be considered for the system.

Ensure that mechanical construction is strong and materials are highly resistant to corrosion.

Keep the variety of material to a minimum.

Examine the structure to be protected and place the air terminals at the position most likely to intercept the lightning strokes (ridges, parapets, other projections, etcetera). Generally, air terminals should be spaced a maximum of 6 to 7.5 m (20 to 25 ft) apart depending on terminal height along ridges, parapets, and other projections. On flat or gently sloping roofs (pitch of $\frac{1}{4}$ or less), additional terminals should be installed at intervals not exceeding 15 m (50 ft) on the flat or sloping areas.

Keep the path to ground from the air terminal as direct as possible, avoiding sharp bends. No bend of a conductor should form an included angle of less than 90 degrees nor have a radius of bend less than 200 mm (8 in).

Provide at least two paths external to the structure to ground for each air terminal. This can be accomplished by ringing the structure with a conductor and attaching multiple down conductors. Structures having a perimeter exceeding 75 m (250 ft) should have one additional down conductor for each additional 30 m (100 ft) in perimeter or fraction thereof. The total number of down conductors should be such that the average distance between down conductors does not exceed 30 m (100 ft).

Connect the down conductors to a point outside the base of the structure (high current density could damage the foundation or slab if ground entry was within the building). A minimum of two connections should be made to a buried grounding system for every structure at a minimum of 0.6 m (2 ft) outside the structure.

Where down conductors pass within 1.8 m (6 ft) of large metal objects, interconnecting conductors should be used at all locations to prevent sideflashes from occurring due to potential difference that could exist during lightning discharges. In all cases, metal objects as high as or higher than surrounding air terminals should be bonded to the lightning-protection system.

Induced electrostatic voltages in isolated, ungrounded objects may cause arcing to ground if a ground path is not provided. If these objects

are within a protected structure, then the objects are adequately shielded.

Keep the resistance of all connections as low as possible.

Tips of air terminals should project a minimum of 250 mm (10 in) above the object protected for a maximum spacing between terminals of 6 m (20 ft). For spacing between terminals of 7.5 m (25 ft), tips of air terminals must extend at least 600 mm (24 in) above structure. Each air terminal exceeding 600 mm (24 in) in height should be supported at a point not less than one-half its height.

For some installations, there may be a requirement that the lightning-protection system be installed under the Underwriters Laboratories Master Label Service. To be a master labeled lightning-protection system, the system must be:

- 1) Installed by an accredited installer of a manufacturer of listed lightning-protection materials.
 - 2) Using materials with the appropriate UL label.
 - 3) Inspected by Underwriters Laboratories.
- (Specific details and requirements can be found in ANSI/UL 96-1981 [8].)

A more detailed description of the air terminal system of lightning protection may be found in the latest revision of ANSI/NFPA 78-1983 [7]. In case of differences between ANSI/NFPA 78-1983 [7], ANSI/UL 96-1981 [8], or this guide, the more restrictive requirement should be followed.

5.3.5 Other Methods of Protection

5.3.5.1 Overhead Ground Wires. Shielding against lightning strokes by use of overhead ground wires is a frequently used method of protection for transmission lines and substation structures and at least the first 600 to 750 m (2000 to 2500 ft) of exposed lines adjacent to the station. For high-voltage transmission lines and substation structures, the shielding angle is usually taken as 30 degrees for a single overhead ground wire.

For extra high-voltage and ultra high-voltage transmission lines, a shielding angle of 30 degrees may not adequately protect the line. Line shielding should be designed such that the shielding failure stroke current I_{max} (the maximum current in a lightning stroke that can bypass the shielding and strike the transmission line directly) is less than the current that will result in a flashover of the line insulation system. Calculation methods are given in "Light-

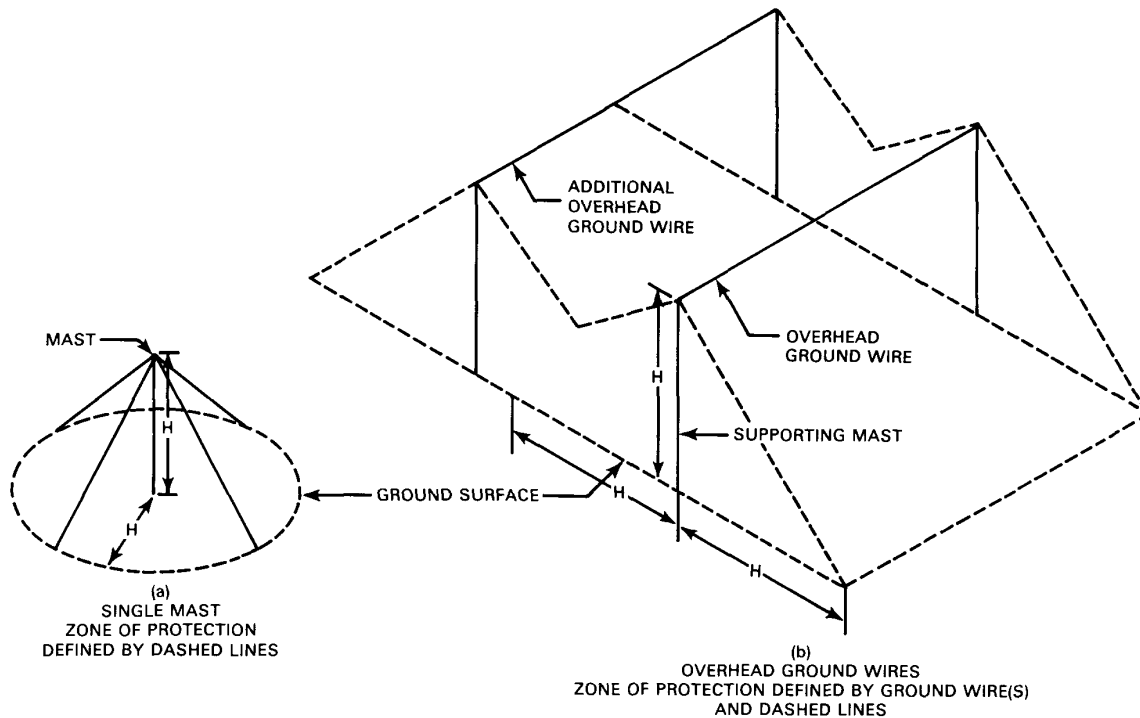


Fig 1
Zone of Protection for Mast Height "H" Not Exceeding 15 m (50 ft)*

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ning Performance I—Shielding Failures Simplified" [9].

5.3.5.2 Masts. The zone of protection of a grounded terminal or mast composed of conducting material and less than 15 m (50 ft) in height is taken as the space enclosed by a cone whose apex is at the highest point of the rod or mast and whose radius at the base, H , is equal to the height of the rod or mast (see Fig 1a).

For masts in excess of 15 m (50 ft), the zone of protection is defined by a 30 m (100 ft) radius arc that passes through the tip of the mast and is tangent to the ground (see Fig 2a). Note that for masts greater than 30 m (100 ft) in height, the 30 m radius arc is tangent to the mast at 30 m above ground. Thus mast height greater than 30 m (100 ft) will not increase the zone of protection.

The space enclosed by the zone of protection

has been found to be substantially immune to direct strokes of lightning. No part of the structure to be protected should extend outside of the zone of protection. If more than one rod or mast is used, the shielded region between them is somewhat greater than the total of the shielded regions of all the rods or masts considered individually. Masts that are separate from the structure to be protected should not be less than the bonding distance or side flash distance, as defined in ANSI/NFPA 78-1983 [7], Sections 3-23 and 3-24, from the protected structure. The masts should be permanently grounded to a ground rod, counterpoise, or ground mat system at the base of the mast and connected to the ground system of the structure to be protected.

5.3.5.3 Masts and Overhead Ground Wires. The zone of protection of overhead ground wires less than 15 m (50 ft) high is con-

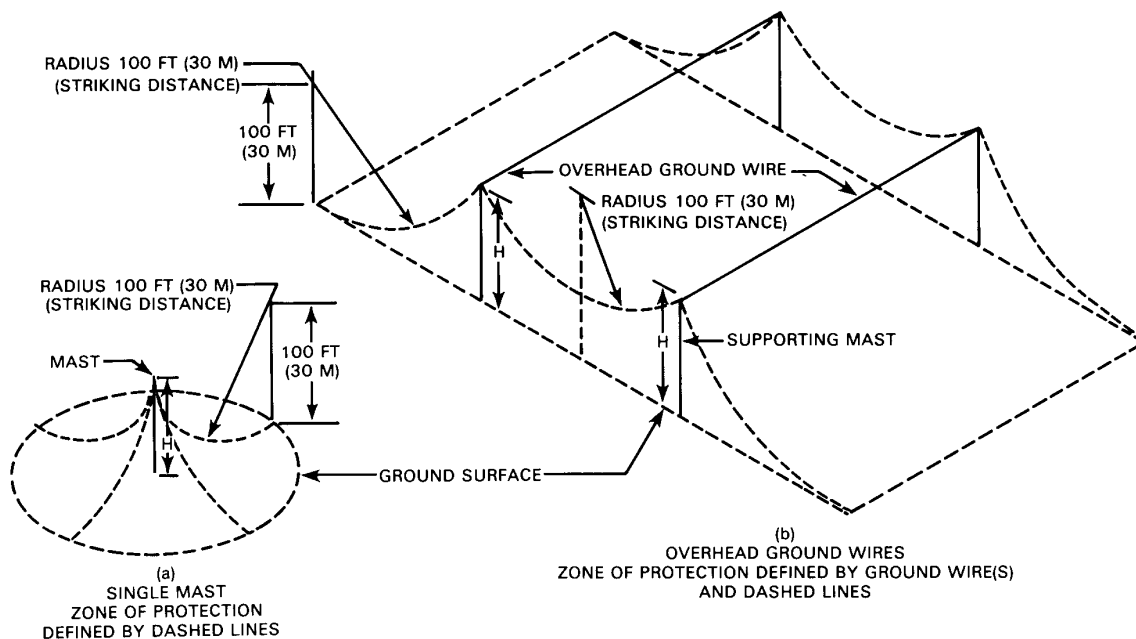


Fig 2
Zone of Protection for Mast Height "H" Exceeding 15 m (50 ft)*

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ventionally taken as a triangular prism or wedge. One half of the base of the wedge (H) equal to the height of the lowest point of an overhead ground wire, has been found to be satisfactory (Fig 1b). For a ground wire more than 15 m (50 ft) above ground, the zone of protection is based on a 30 m (100 ft) radius (Fig 2b). The supporting masts should have the same clearance from the protected structure as already given for masts alone.

The minimum clearance between overhead ground wires and the highest projection of the structure should not be less than the bonding distance or side flash distance, as defined in ANSI/NFPA 78-1983 [7], Sections 3-23 and 3-24.

Masts used either separately or with overhead ground wires may be of wood, provided the mast is equipped with a proper down conductor. An approved type of air terminal should be securely mounted to the top of the pole extending 0.6 m (2 ft) above the top of the pole and connected to

ground electrodes. In case of an overhead ground wire system, the pole guy wire if not insulated may be used as the down conductor. It is usually recommended, however, that a separate down conductor be used. For metallic masts, the air terminal and the down conductor are not required, but the masts should be grounded directly to the grounding system.

5.3.5.4 Structure Grounding. Structure grounding with no other protection can be used on all metal structures of sufficient strength and mass to withstand a direct stroke without burnthrough or other damage. It has been demonstrated that structures constructed of exposed steel plate with a minimum thickness of 4.8 mm ($\frac{3}{16}$ in) will provide this type of protection.

5.3.5.5 Other Tall Structures. Shielding against lightning strokes by use of other tall structures can be used if a structure is within the zone of protection provided by another structure. In these instances, no other means of pro-

tection from lightning is required. Areas of lower roofs and structures protected by higher structures may be found in ANSI/NFPA 78-1983 [7]. Generally, buildings that do not exceed 7.5 m (25 ft) in height are considered to protect lower structures in a one-to-two zone of protection. Structures that do not exceed 15 m (50 ft) in height are considered to protect lower structures in a one-to-one zone of protection. Buildings that exceed 15 m (50 ft) in height are considered to protect lower structures if the lower structure lies in the area beneath an arc 45 m (150 ft) in radius where the arc passes through the highest point of (or is tangent to) the taller structure and is tangent to the ground or roof of a lower structure.

5.3.6 Materials Used in Lightning Protection. Lightning-protection equipment should be a very low-maintenance item and care should be exercised in choosing the proper material to fit the conditions of installation.

Materials are classified into two categories that relate to the protected structure height.

5.3.6.1 Materials, Class I. A Class I building is one that is less than 23 m (75 ft) in height.

Table 1 gives minimum sizes for air terminals and main and secondary conductors. Secondary conductors that are used for bonding and interconnecting metallic bodies to the main conductor and that will not be required to carry the main lightning current may be reduced a size but should not be less than 6 AWG copper or equivalent. Conductors for interconnection to metal water systems, steam or hot water heating systems, or other metallic masses having a low resistance to ground should be main conductor size.

5.3.6.2 Materials, Class II. A Class II building is one that is more than 23 m (75 ft) in height or one that has a structural steel frame of any height whose steel may be substituted for lightning down conductors.

Table 2 gives minimum sizes for air terminals and main and secondary conductors for Class II structures. Systems on these structures should be installed in accordance with requirements of Class I and, in addition, shall comply with the following requirements. If part of a structure is under 23 m (75 ft) in height, the following requirement for air terminals and conductors should apply only to the sections over 23 m in height. Class II conductors installed on parts of a structure exceeding 23 m (75 ft) in height should be connected to ground and also interconnected with the rest of the system. Only metal splicers and connectors welded or secured with bolts are acceptable for use on Class II structures.

5.3.6.3 Conductors. Conductors should be constructed of metal strands, solid strip, solid wire, or tubular bars of equal cross-sectional area and conductivity. The usual conductor material is copper or lead-covered copper.

When aluminum down conductors are used, they should be terminated 0.5 m (18 in) above ground and at that point connected to copper with an acceptable bimetal connector. Avoid use of aluminum where any alkaline base is present including installations on alkaline-based paints. Aluminum conductors, air terminals, or fasteners made of aluminum should not be used on copper roofing or any other copper surface. Bare aluminum conductors should never be buried in earth or embedded in concrete.

Table 1
Class I Material Requirements*

Type of Conductor		Copper		Aluminum	
		Standard	Metric	Standard	Metric
Air terminal, solid	Minimum diameter	3/8 in	9.5 mm	1/2 in	12.7 mm
Air terminal, tubular	Minimum diameter	5/8 in	15.9 mm	5/8 in	15.9 mm
	Minimum wall thickness	0.033 in	0.8 mm	0.064 in	1.6 mm
	Minimum size each strand	17 AWG		14 AWG	
Main conductor, cable	Weight per length	187 lb/1000 ft	278 g/m	95 lb/1000 ft	141 g/m
	Cross section area	57 400 cm	29 mm ²	98 600 cm	50 mm ²
Main conductor, solid strip	Thickness	16 AWG		14 AWG	
	Width	1 in	24.4 mm	1 in	25.4 mm
Secondary conductor, cable (solid or stranded)	Minimum size each strand	17 AWG		14 AWG	
	Cross section area	26 240 cm		41 000 cm	
Secondary conductor, solid strip	Thickness	16 AWG		14 AWG	
	Width	1/2 in	12.7 mm	1/2 in	12.7 mm

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Table 2
Class II Material Requirements*

Type of Conductor		Copper		Aluminum	
		Standard	Metric	Standard	Metric
Air terminal, solid	Minimum diameter	½ in	12.7 mm	¾ in	15.9 mm
	Minimum size each strand	15 AWG		13 AWG	
Main conductor, cable	Weight per length	375 lb/1000 ft	558 g/m	190 lb/1000 ft	283 g/m
	Cross section area	115 000 cm	58 mm ²	192 000 cm	97 mm
Secondary conductor, cable (solid or stranded)	Minimum size each strand	17 AWG		14 AWG	
	Cross section area	26 240 cm		41 100 cm	
Secondary conductor, solid strip	Thickness	16 AWG		14 AWG	
	Width	½ in	12.7 mm	½ in	12.7 mm

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Copper cable, copper air terminals, and copper or bronze fasteners should not be used on aluminum roof, aluminum ventilators, or any other aluminum surfaces.

5.3.6.4 Air Terminals. Air terminals should be of solid or tubular rods. The base of the terminal should have a conducting area of not less than the terminal point. Air terminals should not support vanes or ornaments having, in any plane, a wind resistance area in excess of 129 cm² (20 in²).

If other than copper terminals are used, they should be constructed of a grade equivalent to the conductor or they should be made of stainless steel, Monel metal, or another equally corrosion-resistant metal.

5.3.6.5 Connectors. Connectors should have sufficient mechanical strength for the application and should provide electrical conductivity equivalent to that of the conductor.

Connectors should be compatible with the conductor on the galvanic scale and thus suitable for use with the conductor material. This requires that a bimetallic connector be used when connections are made between two materials such as aluminum and copper.

5.3.6.6 Fasteners. Fasteners should be made of a material that is compatible on the galvanic scale with that of the conductor.

Fasteners should provide mechanical strength and should not be subject to breakage or fatigue.

5.3.6.7 Ground Terminals. Ground terminals (rods) should be not less than 2.4 m (8 ft) long and not less than 12.7 mm (½ in) in diameter. Rods should be copper-clad steel, solid copper, or stainless steel.

5.3.7 Suggested Means of Protection for Various Types of Structures. Once a decision is made to protect the structures (based on fac-

tors in 5.3.3), the next action is to select the method of protection. The following paragraphs suggest methods to aid in the design and installation of protection systems only. Provisions of most codes are taken into account, but the designer should check those codes that specifically apply to his job.

5.3.7.1 Chimney and Stacks. For lightning protection, metal stacks should be provided with a minimum of two ground conductors directly opposite on a diameter from the base of the metal stack to the ground grid.

Nonmetallic chimneys of brick and reinforced concrete should have air terminals projecting not less than 0.5 m (18 in) nor more than 0.75 m (30 in) unless provided with adequate structural support above the upper elevation of the chimney, with a recommended projection of at least 0.6 m (24 in). These air terminals should be electrically connected together by a conductor that forms a closed loop near the top of the chimney. If there is a metal crown, the terminals should be connected to it. Air terminals should be uniformly distributed around the chimney at intervals not exceeding 2.4 m (8 ft). Air terminals should be securely fastened to the top of the chimney. Chimney air terminals may not be required if there is a metal crown greater than 9.5 mm (¾ in) thick that completely covers the top of the chimney perimeter and is suitably bonded and grounded.

All exposed copper or bronze equipment on the upper 7.5 m (25 ft) of chimney should have a minimum thickness of 1.6 mm (1/16 in) lead coating to resist corrosion by sulphurous products. Such parts include conductors, connectors, splices, fittings, and attachments. Exposed stainless steel or Monel metal equipment need not be lead covered.

At least two down conductors should be provided on opposite sides of the stack from the encircling conductors interconnecting air terminals or from the metal crown. Horizontal conductors should be fastened at intervals not exceeding 0.6 m (2 ft), and vertical conductors should be fastened at intervals of 1.2 m (4 ft). Mechanical protection should be provided for down conductors that might be damaged by personnel or equipment. And on reinforced concrete stacks, the down conductors should be bonded to the reinforcing steel at the top and bottom of the structure.

On chimneys over 60 m (200 ft) in height, an additional encircling collar interconnecting down conductors should be provided at mid height.

Where chimneys have metal liners, ladders, or both, they should be connected to the lightning-protection system at their upper and lower ends.

The above paragraphs have addressed stacks and chimneys used primarily for combustion gases and ventilation. Where ventilating stacks emit explosive gases or dust, the terminals should project above the structure opening at least 1.5 (5 ft). If these explosive mixtures are emitted under forced draft, the terminals should project at least 4.6 m (15 ft) above the opening.

5.3.7.2 Metallic Fences. Grounding of fences is important because the general public can be exposed to dangerous touch voltages. Fences included within the ground grid area should have a conductor parallel to the fence on the outside at a distance of 0.5 to 1.5 m (1½ to 5 ft), with 1 m (3 ft) generally recommended, and the fence and conductor should be bonded together and to the ground grid at frequent intervals.

Where a fence is not included in the ground grid area, reference should be made to the precautions in ANSI/IEEE Std 80-1986 [1]. In order to decrease the length of fence that could become energized during lightning discharges and power system faults and therefore decrease the safety hazard to the plant personnel and general public, the fence frame and fabric in long runs such as around the plant perimeter should have insulating sections at approximately 150 m (500 ft) intervals. An acceptable insulating section may be created by installing two breaks in the fence approximately 3 m (10 ft) apart. A break would consist of two posts side by side such that an open space of at least 25 mm (1 in) exists

between the two posts when the final installation is completed.

The practice of providing a driven ground rod at each fence post for approximately 7.5 m (25 ft) either side of the transmission line outer conductors with a grounding conductor parallel to the fence and connected to the rods may be employed in grounding the station perimeter fence or the substation fence to provide an immediate and direct path to earth in the event of a fallen line.

5.3.7.3 Metal Tanks. Metal tanks are generally considered protected from lightning if joints are of welded, bolted, or riveted construction and if the thickness of the steel plate is at least 4.8 mm (3/16 in) thick in the strike area. At least two ground conductors from the base of the tank to the ground grid should be provided. Where flammable liquids are stored, the roof seams should be gastight and provide electrical continuity. Where these provisions cannot be met, the structure should be grounded for touch voltage and protected from lightning by overhead ground wires or a mast system. In all cases, tanks with nonmetallic roofs are not self-protecting and should be protected by air terminals, masts, or overhead metal ground wires. Pressure vessels should be given special consideration regardless of thickness because of possible structural weakening resulting from a direct lightning stroke.

5.3.7.4 Buildings With Structural Metal Framing. Buildings with structural metal framing may be protected by installing air terminals on the high points of the structure and connecting the metal frame to the ground system on the lower end. In cases where the structural steel serves as the main conductors of the lightning-protection system, the steel has to be electrically continuous.

5.3.7.5 Substation Structures. Substation structures are generally protected from lightning by an overhead ground wire and mast system, while touch voltage protection is provided by bonding the structure and equipment to the ground mat. ANSI/IEEE Std 80-1986 [1] provides reference for grounding in the substation area.

5.3.7.6 Reactor Building. Reactor buildings in nuclear generating stations should be protected by an air terminal system designed in accordance with the criteria listed in 5.3.4.

5.3.7.7 Cooling Towers. Cooling towers should be equipped with an air terminal light-

ning-protection system. Where reinforced concrete construction is used, the metal rebar should be made electrically continuous (tie wires are adequate) and connected to the down conductors at the top and bottom of the tower. When precast concrete sections are used, it is often not practical to bond the rebar between precast sections. Hence on precast structures, bonding of the down conductor to the rebar is not required.

5.3.7.8 Microwave and Meteorological Towers. Microwave and meteorological towers should be protected by an air terminal system. A single long air terminal or multiple short air terminals may be used, depending on the tower structure. If a single air terminal is used, all portions of the towers to be protected should lie within the zone of protection described in 5.3.5. If short air terminals are used, they should extend 0.6 m (24 in) above the structure protected and should be spaced no more than 2.4 m (8 ft) apart. For the multiple air terminal system, a minimum of two down conductors should be used. For a long single air terminal design, only one down conductor is required. The down conductors should be electrically connected to the tower at the top and bottom of the tower. Down conductors should be connected to the tower grounding system.

5.3.8 Grounding for Static Discharges Other Than Lightning

5.3.8.1 Coal-Handling Areas. In coal-handling areas, exposed noncurrent-carrying metal parts of equipment such as frames or metal exterior of motors, lighting fixtures, other utilization equipment, cabinets, and conduit should be grounded as specified in 5.2.

5.3.8.2 Hydrogen Storage Areas. In hydrogen storage areas, the hydrogen container and associated piping should be electrically continuous and grounded. Additional information on hydrogen systems may be found in ANSI/NFPA 50A-1984 [5].

5.3.8.3 Nonconductive and Semiconductive Equipment and Material. For guidance in control of static electricity on nonconductive equipment such as conveyors and on nonconductive or semiconductive material, refer to ANSI/NFPA 77-1982 [6].

5.4 Grounding of Buried Structures

5.4.1 General. The purpose of this section is to provide guidance for the method of protecting personnel and animals from excessive step and touch transfer voltages caused by ground cur-

rents flowing in buried conducting materials during a fault. Additional considerations are required in the design of grounding for installations where cathodic protection systems are used.

Subsurface conducting material, such as pipe lines that may run from the generating station ground grid area to points remote from the ground grid, can allow transfer of the ground grid voltage to remote points. Grounding of buried structures in accordance with recommendations of this document will minimize the transfer of voltage between station ground grid and remote points.

5.4.2 Buried Welded Piping: Gas, Fuel Oil, or Water. Buried welded gas, water, or oil lines connected to the generating station equipment should be grounded by connection to the station ground grid or through building steel where the lines emerge from the ground. Where the welded pipeline passes outside of the ground grid area, an insulating section should be installed in the pipeline. The insulating section will separate the station ground grid voltage on the station end of the pipe from remote earth voltage on the other end of the pipe. The insulating section should be of the order of 9 m (30 ft) in length to avoid shunting by the adjacent soil. It should be recognized that insulating pipe joints may not be effective where pipes are carrying conducting fluids.

It is usual practice to coat all buried steel pipe for protection from corrosion.

If there is a fence surrounding the generating station and the fence is grounded to the station ground grid and the buried pipe crosses the fence, then the insulating section in the buried pipe should be installed outside the fenced area.

If the fence is remote from the station and the pipe also contains insulating joints near the station, additional insulating joints are not required if the pipeline crosses under the fence. Figure 3 indicates several pipeline installations where fence and railroad lines run parallel or normal to buried pipelines.

5.4.3 Buried Cast-Iron Piping. All buried cast-iron pipes in the generating station ground grid area should be connected to the station ground. A copper bonding jumper should be installed across each pipe joint to make the pipe electrically continuous. The bonding jumper should be exothermically welded to the cast-iron pipe. All copper connections to the pipe should preferably be insulated from earth to prevent

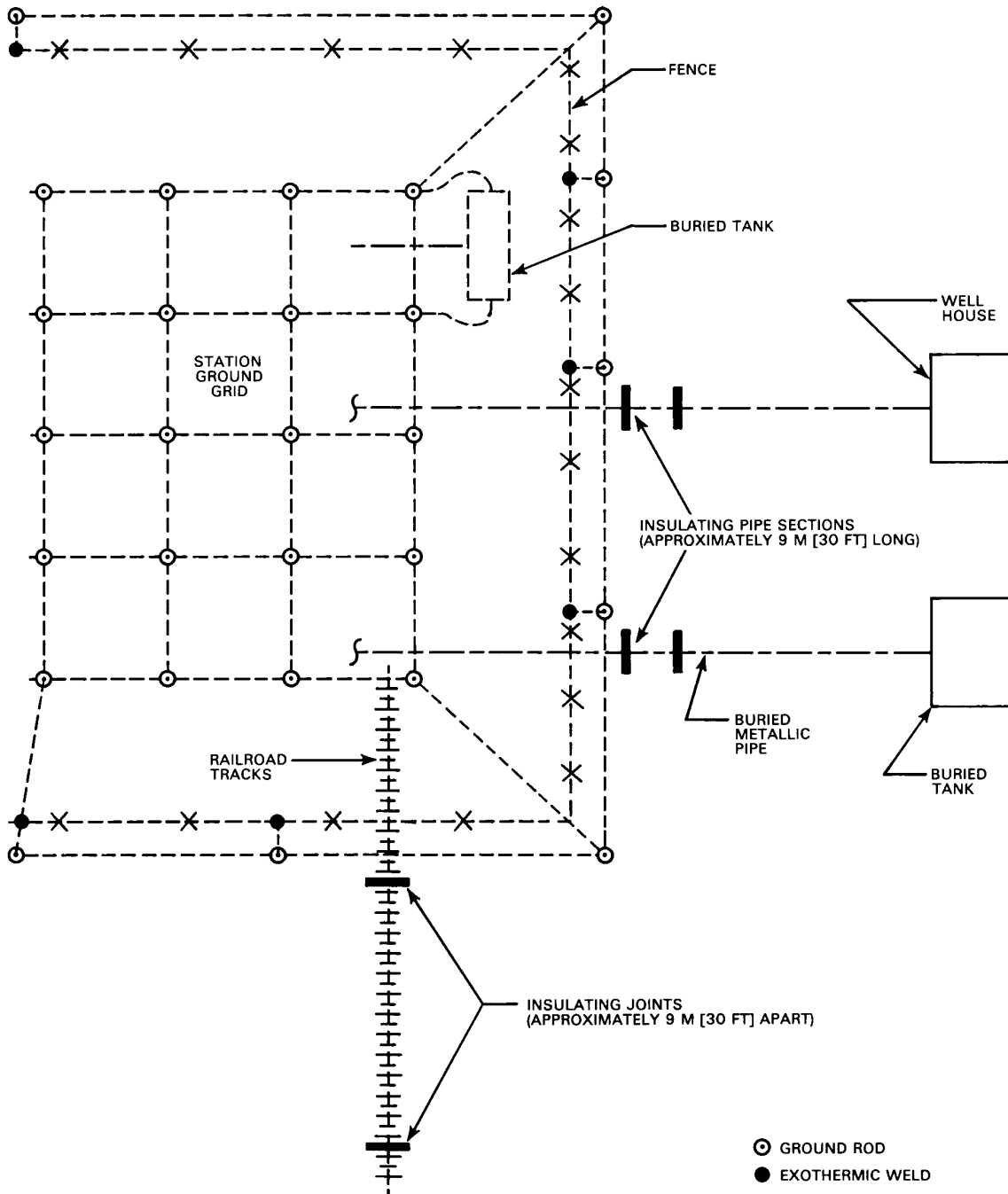


Fig 3
Generating Station Buried Piping and Tanks

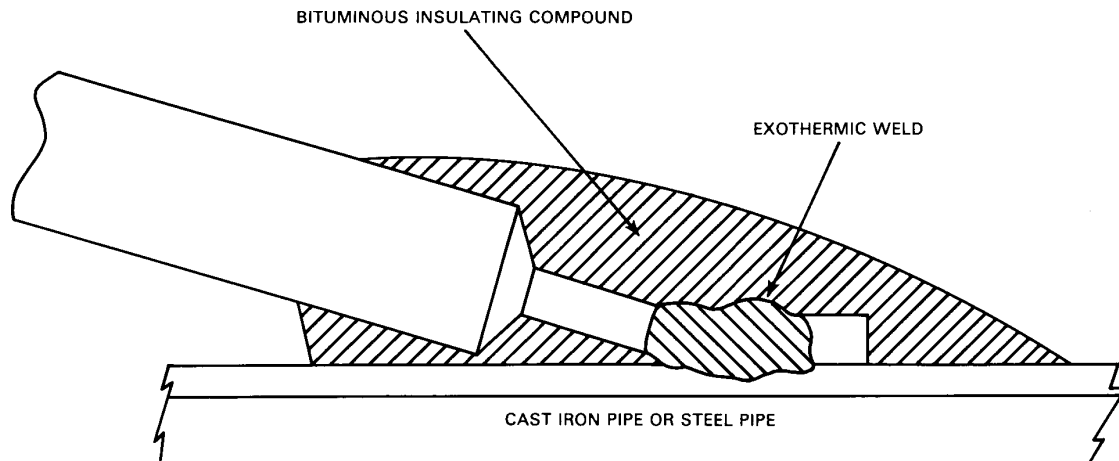


Fig 4
Electrical Connection to Cast Iron Pipe or Steel Pipe

galvanic corrosion of the pipe. Figure 4 shows a suggested method of connecting the bonding jumper to cast-iron piping.

The cast-iron pipe should contain insulating sections, if needed, and be grounded similarly to welded steel pipe, as discussed in 5.4.2.

5.4.4 Station Reinforcing Steel. The following is an extract from ANSI/IEEE Std 142-1982 [3], Section 4.2.4:

"Concrete below ground level is a semiconducting medium of about 30 ohm-cm resistivity at 20 °C, or somewhat lower than the average earth resistivity. Consequently, in earth of average or high resistivity, the encasement of rod or wire electrodes in concrete results in lower resistance than when a similar electrode is placed directly in earth. This is due to a reduction of the resistance of the material closest to the primary electrode, in much the same manner as chemical treatment of the earth reacts near the electrode. While it is seldom justifiable to excavate or drill holes for the placement of concrete for this purpose, the widespread use of steel reinforcing bars in concrete foundations and footings provides a ready-made supply of grounding electrodes at structures utilizing this type of construction. It is only necessary to bring out an adequate electrical connection from a main reinforcing bar of each such footing for attachment to the building ground bus or structural steel. . . .

"Each such *footing electrode* has a resistance equal to or lower than that of a driven rod of equal depth. The large number of such footings inherent to buildings will provide a net ground resistance considerably lower than that normally provided by other made electrode methods. . . ."

Test results and design data for determining ground resistance of single and multiple concrete-encased footing electrodes are given in "The Use of Concrete-Enclosed Reinforcing Rods as Grounding Electrodes" [10].

In order to use reinforcing steel as part of the ground grid, an effective metallic connection between the reinforcing steel bars and the structural steel should be established or else damage to the concrete will be likely. A typical arrangement for grounding of reinforcing steel of a concrete footing to station ground is shown in Fig 5.

When reinforcing steel is connected as part of the ground grid, it should be recognized that there may be some risk of damage to structural concrete for high values of ground current.

5.4.5 Buried Tanks. Buried tanks are usually coated for protection from corrosion. If the tank is in the station ground grid area where the earth surrounding the tank would approach the ground grid voltage during a fault, then the tank should be tied to the ground grid with a minimum of two ground connections, as indicated in

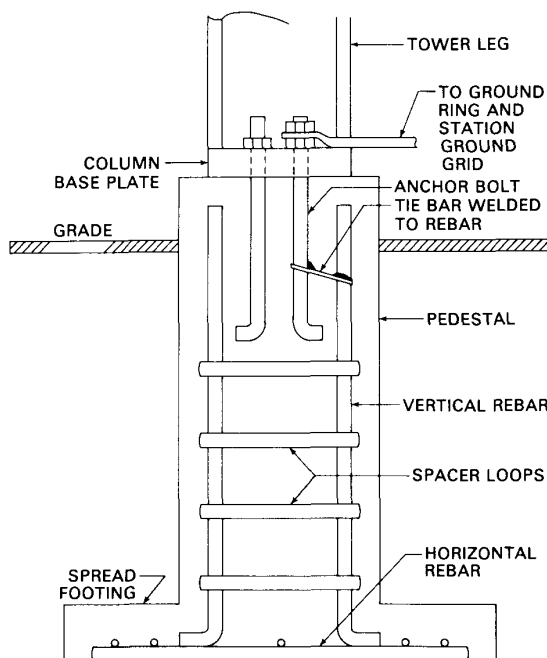
Fig 3. Where tanks are grounded through the piping system, these additional ground connections may not be required. In this case, the piping should be electrically continuous and connected to the ground grid.

If the buried tank is outside of the two insulating joints, as indicated in Fig 3, the tank should not be connected to the station ground grid but an insulating section should be installed in the pipeline, as indicated in Fig 3.

5.4.6 Buried Cables. Buried or overhead cables entering a generating station from off site, or in some cases from other isolated ground grids on the site such as in communication systems and control cables from substations, should be protected against high voltages during transmission system ground faults, lightning stroke, or switching surges. In the case of leased communication cables, a mutually agreeable method for protective equipment to be installed by either party is the generally accepted practice.

The protection of communication systems is covered in ANSI/IEEE Std 487-1980 [4]. This guide should be referred to for the design of any type of communications cables entering generating stations.

Fig 5
Tower Leg Grounding



Multiconductor cables for control, instrumentation, relay protection, and telemetering entering the generating station from the high-voltage substation or transformer yard generally have overall shields. In order to minimize the effect of high-energy, high-frequency transients on cables in these applications, the shield should be grounded at both ends and preferably also at intermediate points. In order to reduce the current carried by the shield, a heavy ground conductor should be provided alongside the shielded cable and should be connected to the generating station and substation ground grids. The substation and generating station ground grids should also be tied together with heavy ground conductors at a number of points in order to limit the voltage difference between the two ground grids during a ground fault in the substation. Where the voltage difference between the substation ground grid and the generating station ground grid is high, voltage stresses are imposed on the cable insulation requiring careful selection of insulation level of control cables between the substation and the generating station. Control cables with 1 kV insulation are used by many utilities for this application.

The shield for low-level signal cables such as telemetering cables should be grounded at the substation end only. The generating station end of these cables should be connected to low-voltage surge-protective devices such as gas tube protector gaps. For a description of gas tubes, see ANSI/IEEE Std 487-1980 [4].

In cases where there is a large separation distance between the ground grids and where there are no hard-wired control connections between the substation and generating station (such as where microwave supervisory links are used), it is not necessary to tie the ground grids together.

5.4.7 Steel Pipe Piles and Steel "H" Piles. Pipe-type steel piles may be used in a generating station. The piles can serve to provide a low ground resistance grid by connecting piles together at their uppermost ends with an annealed bare copper conductor exothermically welded to the top of the pile. The copper bonding jumpers between the piles should be encased in concrete. If the copper bonding jumpers are exposed in earth, then they should be jacketed with a water-resistant sheath. This will prevent galvanic action between bare copper and the steel piles.

In some generating stations, steel "H" shapes are used as piles. They also serve as efficient ground rods below the generating station. The

steel "H" shapes should be connected together in a similar manner as indicated for the pipe-type steel piles.

Another type of pile used is a thin steel shell-type with a concrete core placed after the shell is driven with a mandrel. The thin steel shell should be considered expendable. Before the pile is driven, a bare copper conductor can be brazed to the side of the steel shell near its lower end. The bare conductor should be fastened to the shell approximately every 2.5 m (8 ft) with a heavy soft steel binding wire.

After each pile is driven, the conductor ground resistance should be measured. In fine soils, the number of bare copper conductors that break away from the piles will be minimal. Satisfactorily grounded piles can be determined by measuring the ground resistance of each conductor. Those conductors with high ground resistance should be abandoned. The conductors with satisfactory resistance should be connected to form a ground grid. Since the pile shells are considered expendable, the copper ground grid could be placed in the soil to further lower the ground resistance.

When building piles are used to augment the grounding system, it is not necessary to connect each and every pile into the grounding system. Piles, like ground rods, are not used efficiently when they are close to one another. It would be satisfactory to connect those piles to the ground grid system, which is located at distances approximately equal to the length of the pile.

6. Bibliography

- [B1] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.
- [B2] ANSI/IEEE Std 141-1986, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants.
- [B3] ANSI/NFPA 70-1987, National Electrical Code.
- [B4] DALZIEL, C. F. A Study of the Hazards of Impulse Currents. AIEE Transactions, vol 72, part III, 1953, pp 1932-43.
- [B5] DALZIEL, C. F. Electric Shock Hazard. IEEE Spectrum, Feb 1972.
- [B6] DAWALIBI, F. and MUKHEDKAR, D. Optimum Design of Substation Grounding in a Two Layer Earth Structure. IEEE Transactions on Power Apparatus and Systems, July/Aug 1974, p. 1023.
- [B7] DEMERS, G. and MUKHEDKAR, D. Ground Grid Design. The Engineering Journal, Engineering Institute of Canada, vol 51, no 2, Feb 1968, pp 36-40.
- [B8] DESIENO, C. F., MARCHENKO, P. O., and VASSELL G. S. General Equations for Fault Currents in Transmission Line Ground Wires. IEEE Transactions on Power Apparatus and Systems, Nov/Dec 1970, pp 1891-1900.
- [B9] A Consolidated Reprint of Articles Published in Electrical Engineering. Originally presented as a Series of Lectures Conducted by the Power and Industrial Group of the New York Section of the American Institute of Electrical Engineers on Grounding Principles and Practices.
- [B10] ENDRENYI, J. Fault-Current Analyses for Station Grounding Design. Ontario Hydro Research Quarterly, Second Quarter, 1967.
- [B11] GOLDE, R. H. The Lightning Conductor. The Journal of the Franklin Institute, Electrical Research Association, Leatherhead, Surrey, England, vol 283, no 6, June 1967.
- [B12] HADDAD, S. Grounding Mats for Power Plants and Substations. Transmission Line and Substation Design Seminar, Chicago, Dec. 10, 1970 (Sargent and Lundy).
- [B13] HAMBURGER, G., Practices for Utility Grounding. IEEE unpublished paper CP64-248.
- [B14] HUEY, R. M. and RAJARATNAM, K. Identification of Electrical Parameters in Large Earth Grids. IEEE Transactions on Power Apparatus and Systems, Jan/Feb 1974, p 187-195.
- [B15] JACQUE, B. Interference Induced into the Auxiliary Wiring of Power Plants and Substation During Faults. 36-01, Extrait de la Conference Internationale des Grands Reseaux Electriques, 1972 (112 boulevard Haussmann, Paris).
- [B16] LARSEN, S. L. and NORDELL, D. E. The Measurement of Substation Ground Resistance and Its Use in Determining Protection for Metallic Communication Circuits. IEEE Transac-